Influence of Temperature on Analytical Description of Cyclic Properties of Martensitic Cast Steel

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Abstract-**The paper presents the results of experimental verification of analytic model of cyclic properties description. The subject of verification was the two-parameter model of Ramberg-Osgood (R-O). The research was carried out at two temperatures using the test pieces of high-chromium martensitic cast steel. The model was assessed by making a comparison of parameters of the hysteresis loop obtained from the calculations using the R-O model. Analysis of the tests and calculations results revealed their diversity depending on the temperature and level of strain covered in the research.**

Keywords-Low Cycle Fatigue; Martensite Cast Steel; Cyclic Properties; Temperature; Ramberg Osgood Model

I. INTRODUCTION

The phenomenon of cyclic strengthening or cyclic weakening of the material, occurring during the process of low cycle fatigue, running at room temperature, is the reason why the process of accumulation of damages realized during the calculations of life is on many occasions considerably hindered [1-3]. However, it gets significantly complicated, when it stops depending only on material properties or loading program, and its course starts to be influenced also by the variable temperature of testing [4 - 7]. The occurring interactions of processes' characteristic for low cycle mechanical fatigue and thermal fatigue may lead to much bigger changes in the cyclic properties of the material. In practice, for both kinds of fatigues for the description of hysteresis loop, the same models of calculation are used [8 - 9]. Using the models worked out for the assumed states of materials for the calculations of fatigue life may lead to a considerable diversity of results of life obtained from the calculations and experimental tests. The aim of the work was experimental verification of analytical description of hysteresis loop at room temperature and elevated temperature – 600 °C.

II. ANALYTICAL DESCRIPTION OF LOW CYCLE PROPERTIES

One of the simplest methods of obtaining hysteresis loop description consists in using the curve of cyclic strain for that purpose. Such a curve can be achieved on the basis of experimental tests joining the vertices of stabilized hysteresis loops determined at different levels of strain. For the analytical description of such a curve, different models are used. Most frequently used model is that of Ramberg-Osgood [10] given below:

$$\frac{\Delta \varepsilon_c}{2} = \frac{\Delta \sigma}{2E} + \left(\frac{\Delta \sigma}{2K'}\right)^{\frac{1}{n'}} \tag{1}$$

where:

n' – cyclic strain-hardening exponent,

K'- cyclic strength coefficient of the cyclic strain curve,

E - Young modulus.

The values of coefficients n' and K' are determined during fatigue tests [11], whilst the value of the material constant E – in the tests of static tension. While determining the parameters n' and K' an assumption is made that the plastic strain ε_{ap} is a power function of stress σ_a expressed below:

$$\lg \sigma_a = \lg K' + n' \lg \varepsilon_{ap} \tag{2}$$

Where: σ_{as} and ε_{ap}- parameters of hysteresis loop from the period of stabilization.

The implemented modification of the Ramberg-Osgood model consisted in adopting an assumption that there was cyclic yield strength σ_{cpl} existing, below which the material was linear elastic, which made it possible to write the Dependence (1) as follows:

$$\frac{\Delta \varepsilon_c}{2} = \frac{\Delta \sigma}{2E} + \left(\frac{\Delta \sigma - \Delta \sigma_{cpl}}{2K'}\right)^{\frac{1}{n'}} \text{ for } \sigma > \sigma_{cpl} \quad \text{ and }$$

$$\frac{\Delta \varepsilon_c}{2} = \frac{\Delta \sigma}{2E} \text{ for } \sigma < \sigma_{cpl} \tag{3}$$

Where: σ_{cpl}- cyclic yield strength.

In literature there are also other descriptions of cyclic strain curve, with single or two-parameter models. One of the simplest and most frequently used methods of obtaining the hysteresis loop description consists in transforming the curve of cyclic strain described with an Equation (1) or (3). The equation of hysteresis loop's rising branch is obtained in this method by multiplying Equation (1) by 2, which can be expressed as follows:

$$\Delta \varepsilon_c = \frac{\Delta \sigma}{E} + 2 \left(\frac{\Delta \sigma}{2K'}\right)^{\frac{1}{n'}} \tag{4}$$

The equation of descending branch is obtained using the Dependence (4) and transforming the coordinate system to the upper vertices of the loop. These dependencies are used in the case of materials, which follow the Masing principle [12]. For the description of hysteresis loop branch for materials, which are not subject to this principle, other equations should be applied [1].

III. DESCRIPTION OF THE RESEARCH

The material for research were test pieces made of high-chromium martensitic GX12CrMoVNbN 9 – 1 cast steel of the following chemical composition (%wt.): 0.12C; 0.47Mn; 0.31Si; 0.014P; 0.004S; 8.22Cr; 0.90Mo; 0.12V; 0.07Nb;

0.04N. The shape and dimensions of a test sample used for research are shown in Fig. 1.

Fig. 1 Test sample for research

The cast steel subject to study was in the as-received condition, i.e. after heat treatment: 1040 ^{o}C/12h/oil + 760 ^{o}C/12h/air + 750 ^{o}C/8h/furnace. After the heat treatment, the examined cast steel was characterized by a typical microstructure of high-tempered martensite with numerous precipitations of carbides/nitrides ($M_{23}C_6$ and MX) as shown in Fig. 2.

Fig. 2 Microstructure of investigated cast steel

The test pieces were subject to oscillatory tension-compression at five levels of total strain amplitude ε_{ac}=0.25; 0.30; 0.35; 0.50; 0.60 %. The tests were carried out at three temperatures (T=20 and 600 °C) on a hydraulic testing machine with the frequency of 0.2 Hz. The values recorded during the tests were strain and loading force for the chosen stress cycles. The assumed time of sampling between the following records made it possible to map the hysteresis loop with 100 points. The fatigue tests were preceded by the static tests of tension, which were performed at three temperatures, similarly as the fatigue tests (20 and 600°C).

IV. RESULTS AND THEIR ANALYSIS

Analysis of the cyclic properties of test pieces of GX12CrMoVNbN9-1 cast steel under the conditions of changing loads was performed using the most important parameters of hysteresis loop having a direct influence on the achieved results. These parameters included: amplitude of plastic strain ε_{ap} and amplitude of stress σ_a. Their values were determined on the basis of instantaneous values of force loading the test piece and its strain, recorded during sampling. In order to determine the parameters: n' and K' from the

Equation (1), the values of σ_a and ε_{ap}, recorded for the chosen stress cycles, were put to analysis. Examples of curves recorded for five levels of strain amplitude at room temperature and at 600 ^{o}C are presented in Fig. 3.

Fig. 3 Changes in stress σ_a as a function of the number of loading cycles: a) T=20 °C, b) T=600 ^{o}C

On the basis of the curves (Fig. 3), it can be concluded that the temperature of testing influences the fatigue life considerably. This influence depends on the level of total strain amplitude ε_{ac}. It is insignificant in the area of the largest strains realized and grows as the level of strain decreases. During the fatigue tests the changes in the basic parameters of hysteresis loop in the function of the number of stress cycles were observed. The character of their changes was very similar. Regardless of the level of strain and temperature, the examined cast steel was characterized by cyclic weakening. The scale of weakening was influenced by the temperature; the growth of temperature resulted in the growth of extent of the cast steel weakening. The issue of cast steel weakening at room temperature and elevated temperatures has been discussed in detail in the works [13, 14]. In order to discuss the influence of temperature on cyclic properties, Fig. 4 illustrates examples of the courses of σ_a changes in the function of the number of

stress cycles at three temperatures and two levels of total strain: ε_{ac}=0.25% and ε_{ac}=0.60%.
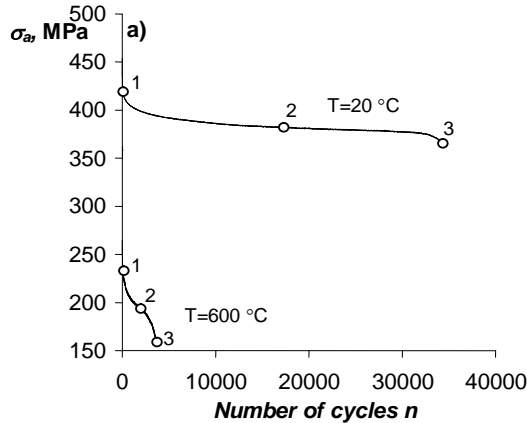

Fig. 4 Stress σ_a as a function of the number of loading cycles: a) ε_{ac} =0.25 %, b) ε_{ac}=0.60%

On the basis of the plotted graphs it is difficult to point to the fatigue life in which the parameters of hysteresis loop can be considered as representative at a given strain level. According to the recommendations included in the work [10], the loop parameters necessary for analytical description of cyclic properties were assumed from the period corresponding to half the fatigue life (n/N=0.5). The loops of hysteresis from this period (points 2 in Fig.4) for two temperatures are shown in Fig. 5 and 6 in the co-ordinate system $\sigma-\varepsilon$ and $\Delta\sigma-\Delta\varepsilon$.

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Fig. 5 Loops of hysteresis obtained at room temperature, n/N=0.5 (point 2-Fig. 3): a) ε-σ, b) $\Delta\varepsilon$-$\Delta\sigma$
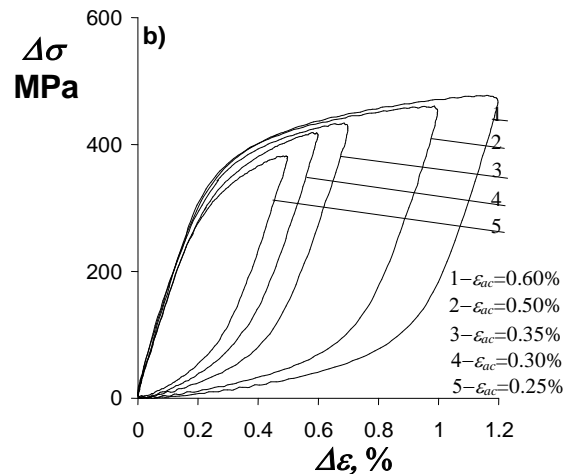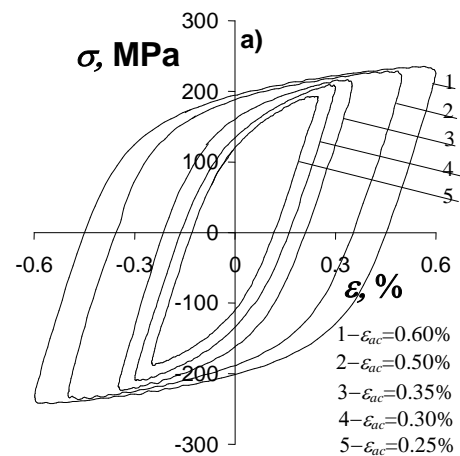

Fig. 6 Loops of hysteresis obtained at the temperature of 600 °C, n/N=0.5 (point 2 –Fig. 3): a) ε-σ, b) $\Delta\varepsilon$-$\Delta\sigma$

On the basis of mutual position of the hysteresis loops it can be stated that the cast steel used for research follows the Masing's principle at room temperature. It is confirmed by the common upper branch for hysteresis loops attached at the beginning of co-ordinate system (Fig. 5b). In the case of elevated temperature (600 °C), the cast steel does not fulfill this principle. At the same time, it proves the limitations in applying some of the calculation models at both: room and elevated temperatures. In order to illustrate the influence of the

assumed fatigue life (n/N=0,5) on the analytical descriptions of the cast steel properties, they were additionally determined in two different fatigue life-periods (points 1 and 3 in Fig. 4). Determining low cycle properties in different life-periods went according to the proposal included in the work [16]. For the analytical description of the dependence between stress σ_a and strain ε_{ap}, the Equation (2) was adopted. Obtained graphs are presented in Fig. 7.

No.	n/N	K', MPa	n'
1	0.05	999.3	0.1232
2	0.50	929.4	0.1198
3	0.95	859.2	0.1117

No.	n/N	K', MPa	n'
1	0.05	553.2	0.1093
2	0.50	474.7	0.1246
3	0.95	552.1	0.1672
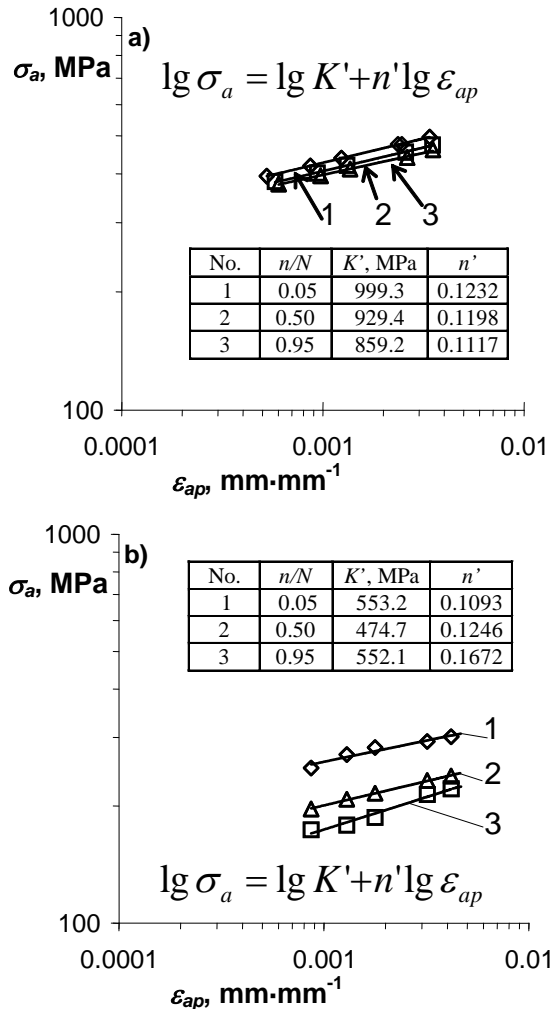
Fig. 7 The graphs of cast steel strain in three life-periods: a) 20 °C, b) 600 °C

Diverse position of the obtained curves is a consequence of changes in the loop parameters in the function of the number of stress cycles observed in Fig. 3 and 4. Achieved curves show that in the case of cast steel there is no constant (invariable) dependence between stress σ_a and strain ε_{ap}. The effect of these changes in hysteresis loop parameters in the function of the number of stress cycles are the diverse values of n' and K' in different life-periods. On the basis of curves illustrated in Fig. 7, it can be noted that along with the growth of temperature, the scope of changes in the parameters of Equation (2) increases, i.e. n' and K' used during calculations of fatigue life. The values of parameters n' and K' – which are diverse depending on n/N - influence the successive characteristics used in the calculations of fatigue life. The curve of cyclic strain described with Equation (1) may be regarded as influential as well. As shown in Fig. 8, apart from the curves of cyclic strain, the curves of static tension obtained at room temperature and at 600 °C are also included. Regardless of the temperature of testing, the curves of cyclic

strain lie below the curves of static tension. This is to prove cyclic weakening of the examined cast steel, irrespective of the testing temperature and level of strain.
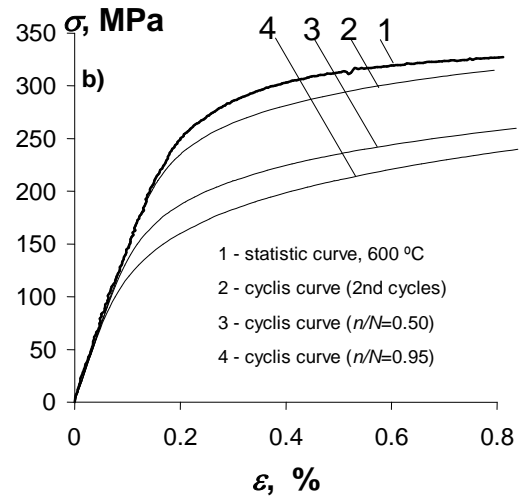

Fig. 8 Curves of static and cyclic strain: a) T=20°C, b) T=600°C

Obtained curves of cyclic strain were used for modeling of the hysteresis loop. For the description of the hysteresis loop branch, Equation (4) was applied. Fig. 9 and 10 present the position of loops obtained during the tests and the loop of hysteresis received from the calculations.
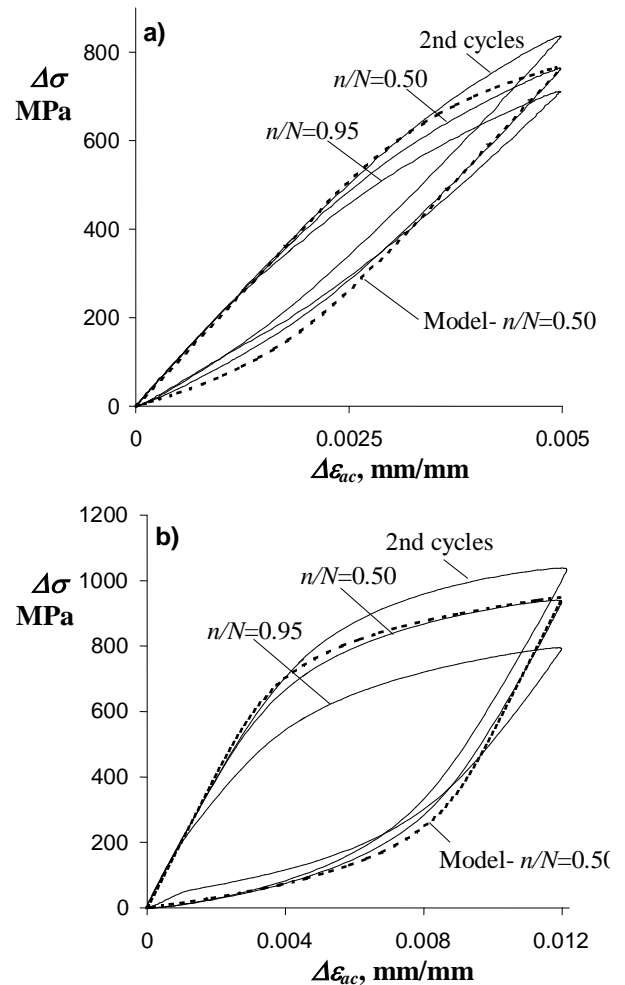

Fig. 9 Hysteresis loops determined from calculations and tests for room temperature: a) ε_{ac}=0.25%, b) ε_{ac}=0.60%
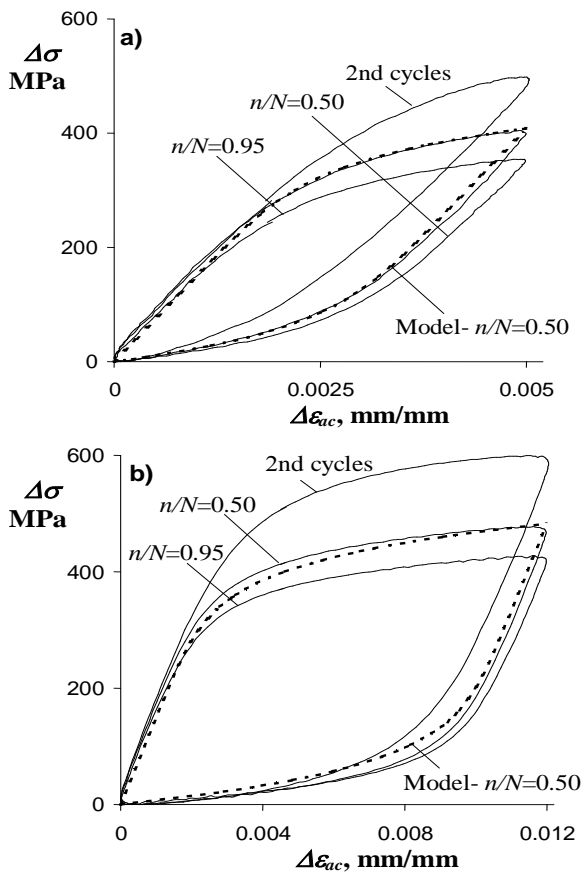
Fig. 10 Hysteresis loops determined from calculations and tests for the temperature of 600 °C: a) ε_{ac}=0.25%, b) ε_{ac}=0.60%

According to the expectations, changes in parameters *n'* and *K'* - depending on *n/N* - influence the results of hysteresis loop mapping. On the basis of mutual location of hysteresis loops achieved in the tests and calculations (Fig.9 and 10) it can be concluded that a model can only map the actual loop for the fatigue life-period for which the parameters *n'* and *K'* were determined.

V. CONCLUSION

Martensitic cast steel during low cycle fatigue at room temperature and at 600 °C is subject to cyclic weakening and does not reveal any evident period of stabilization. The fatigue life of martensitic cast steel is influenced not only by the level of strain, but also by the temperature of testing. The influence of temperature on the fatigue life depends on the level of strain. It is insignificant in the area of very big loads and increases as the level of strain decreases.

In the analytical model of description of hysteresis loop, the parameters determined during changing load are used (*n'* and *K'*). The appearing changes in the parameters of hysteresis loop and the lack of stabilization period of the cast steel at room temperature and at 600 °C are what make it difficult to determine the basic material data, which depend on the fatigue life-period assumed for their determining. Assuming them from the period corresponding to half the fatigue life makes them non representative for the whole period of fatigue life, since they map only the instantaneous cyclic properties of the cast steel.

Along with the growth of testing temperature, there is an increase in the scope of changes in hysteresis loop parameters, and thereby in the very scope of parameters *n'* and *K'*

determined during fatigue tests. The occurring changes in cyclic properties of the cast steel (especially at elevated temperature) can make the mapping during hysteresis loop modeling, with the usage of invariable material data, considerably difficult.

The differences occurring at room and elevated temperature between hysteresis loop obtained from tests and hysteresis loop obtained from calculations are the cause of significant differences in life, which may appear in the calculations of fatigue life in strain or stress approach. This results from the fact of multiple (iterative) usages of material data, which differ a lot from their actual values, during fatigue damage summation.

REFERENCES

[1] A. Fatemi, L. Yang, "Cumulative Fatigue Damage and Life Prediction Theories: A Survey of the State of the Art for Homogeneous Materials", Inter. Journal of Fatigue, vol. 20(1), pp. 9-34, 1998.

[2] S. Mroziński, "The influence of loading program on the course of fatigue damage cumulation", Journal of Theoretical and Applied Mechanics vol. 49, No. 1, pp. 83-95, 2011.

[3] S. Mroziński, J. Szala, "Problem of cyclic hardening or softening in metals under programmed loading", Scientific Problems of machines operation and maintenance, Vol. 45, pp. 83-96, 2010.

[4] D. M. Li, K. W. Kim, C. S. Lee, "Low cycle fatigue data evaluation for a high-strength spring steel", Inter. Journal of Fatigue, vol. 19(8-9), pp. 607-612, 1997.

[5] K. Mathis, Z. Trojanova, P. Lukac, „Hardening and softening in deformed magnesium alloys", Mater. Sc. Eng. A, vol. 324, pp. 141-144, 2002.

[6] M.G. Moscato, M. Avalos, I. Alvarez-Armas, C. Petersen, A. F. Armas, "Effect of strain rate on the cyclic hardening of Zircaloy-4 in the dynamic strain aging temperature range", Mater. Sc. Eng. A, vol. 234-236, pp. 834-837, 1997.

[7] A. Nagesha, M. Valsan, R. Kannan, K. R. Bhanu Sankara, S. L. Mannan, "Influence of temperature on the low cycle fatigue behaviour of a modified 9Cr-1 Mo ferritic steel", Inter. Journal of Fatigue, vol. 24, pp.1285-1293, 2002.

[8] M. Nagode, M. Hack, "An online algorithm for temperature influenced fatigue life estimation: stress-life approach", Inter. Journal of Fatigue, vol. 26, pp.163-171, 2006.

[9] M. Nagode, M. Zingsheim, "An online algorithm for temperature influenced fatigue life estimation: strain-life approach", Inter. Journal of Fatigue, vol. 26, pp.155-161, 2004.

[10] ASTM E606-92: Standard Practice for Strain -Controlled Fatigue Testing.

[11] W. Ramberg, W. R. Osgood, "Description of stress-strain curves by three parameters", NACA, Tech.Note, No 402, 1943.

[12] G. Masing, „Eigenspannungen und Verfestigung beim Messing", in *Proc. of the 2nd Inter. Congress of Appl. Mechnics*, Zurich 1926, pp. 332-335.

[13] S. Mroziński, G. Golański, "Low cycle fatigue of GX12CrMoVNbN9-1 cast steel at elevated temperature", Journal of Achievements in Materials and Manufacturing Engineering, vol. 49, 1, pp. 7-16, 2011.

[14] G. Golański, S. Mroziński, "Fatigue life of GX12CrMoVNbN9-1 cast steel in the energy-based approach", Advanced Materials Research, vol. 396-398, pp. 446-449, 2012.

[15] G. Golański, K. Werner, S. Mroziński, "Low cycle fatigue of GX12CrMoVNbN9-1 cast steel at 600ºC temperature", Advanced Materials Research, vol. 396-398, pp. 326-329, 2012.

[16] S. Mroziński, A. Lipski, "Method of Low-Cycle Fatigue Test Results Processing", Physicochemical Mechanics of Materials, vol. 1, pp. 79-83, 2012.